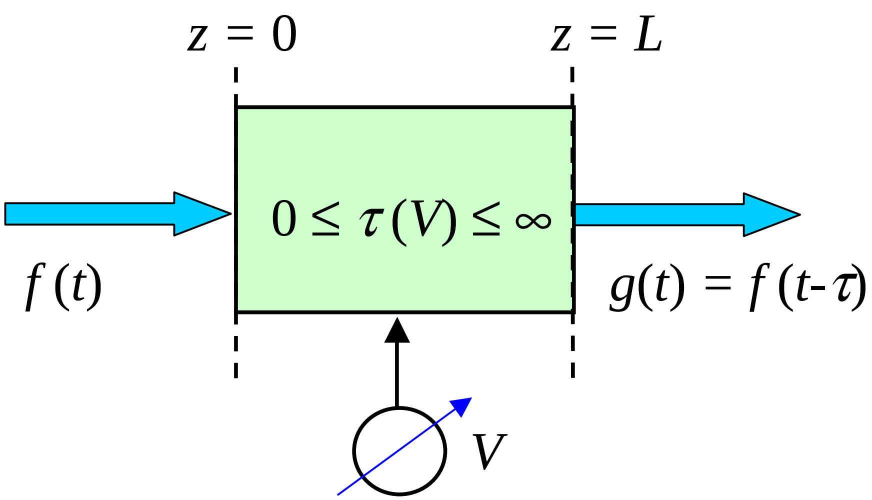
Variable Slow Light Devices for Controllable Optical Memory

Connie Chang-Hasnain
EECS, University of California, Berkeley
Shun-Lien Chuang
EECS, University of Illinois Urbana-Champaign

Definition of Optical Buffers

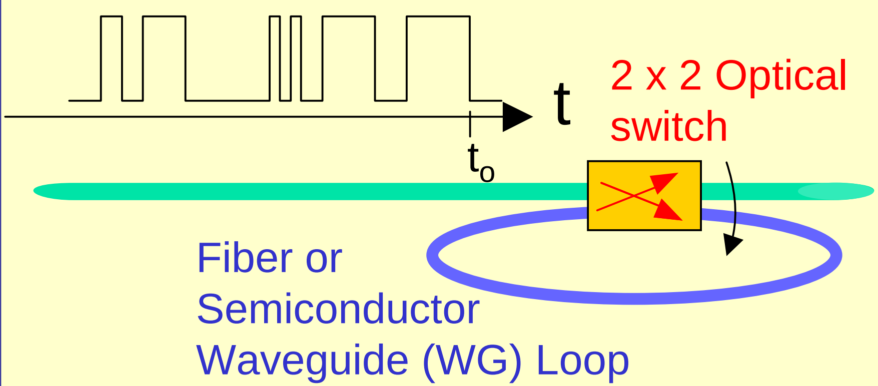
- Both input and output are optical data stream.
- Application will determine device requirements
  - τ controllable within a certain range by an external source
  - Turn on and turn off time: a few bits may be tolerable
  - Size and room temperature operation
  - Storage (how long it can store) and capacity (how many bits it can store) should be independent parameters.



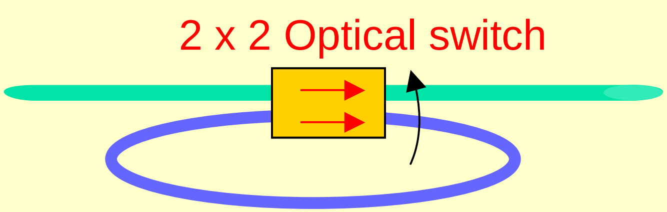
Fixed Optical Buffer with Fiber or WG Loop

To Store

1. Set switch to “X position” and let data to enter the loop

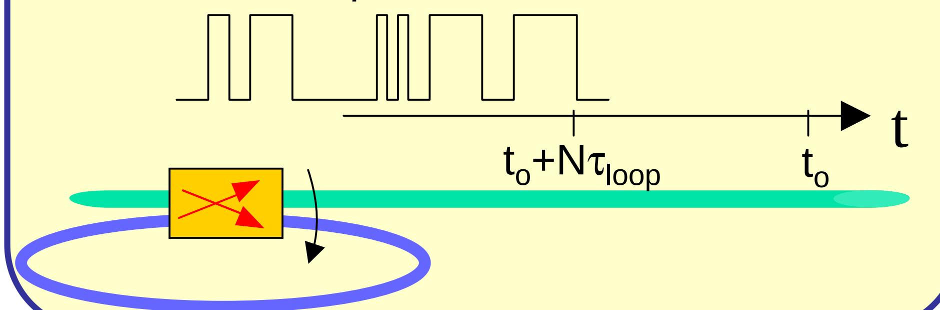


2. After the data completely enter the loop, set switch to “II position” and allow data to recirculate in the loop.



To Release

1. Set switch to “X position” and let data to leave the loop

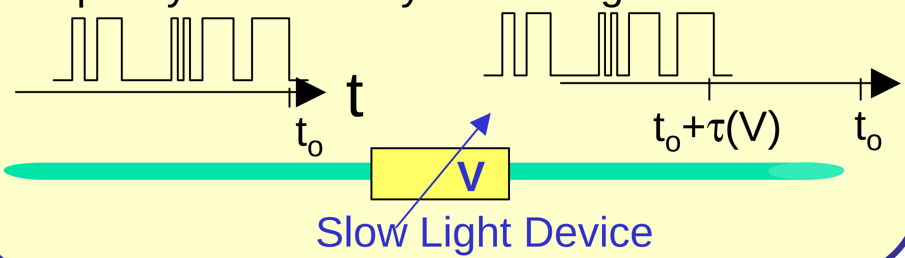


Attributes		Fiber	Semi. WG
Storage (how long)	$N\tau_{loop}$	1ns – 1s	1ps – 1s
Capacity (how much)	τ_{loop}	1ns – 10 μs	1ps – 1 ns
Response	τ_{loop}	1ns – 10 μs	1ps – 1 ns
Size		0.2 m – 2 km	0.01 – 10 cm
Integration		NA	Yes

Variable and Compact Optical Buffer with Slow-Light Device

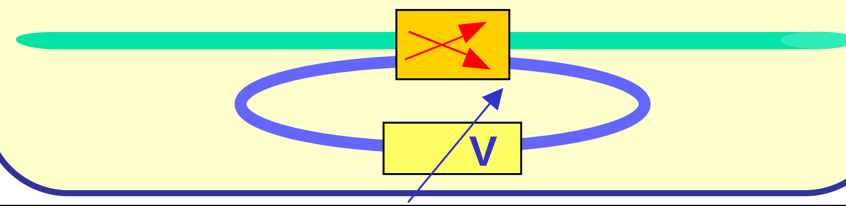
Single Pass Configuration

Vary the slow down factor in slow light device using an external source to vary storage. Capacity is limited by the storage time.



Loop Configuration

Significantly lengthen the storage without compromising response time. Decouple storage and capacity.

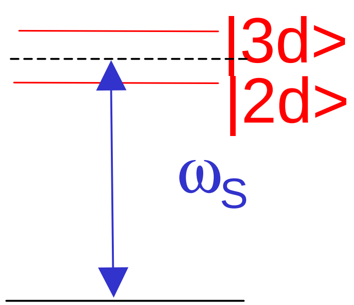


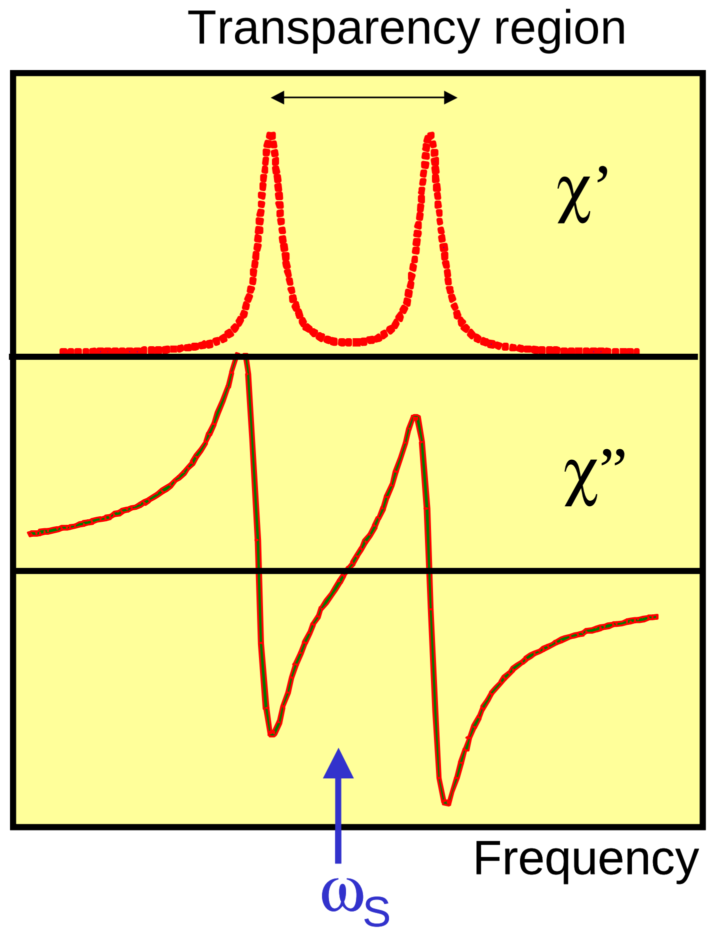
Attributes		QD-EIT	Dispersive WG
Storage (how long)	Variable $\tau(V)$	10 ns – 1 µs	10 ns
Capacity (how much)	Variable $\leq \tau(V)$	10 ns – 1 µs	10 ns
Response		<0.3 ps	Instantan-eous
Size		1 cm	1 cm
Integration		Yes	Yes

Attributes		QD-EIT	Dispersive WG
Storage	$N\tau(V)$	10ns – 1s	10 ns – 1s
Capacity	Variable $\leq \tau(V)$	10 ns – 1 µs	10 ns
Response		<0.3 ps	instantaneous
Size		1 cm	1 cm
Integration		Yes	Yes

Electromagnetically Induced Transparency (EIT)

Coherent Interference of Electronic States and Optical Beams





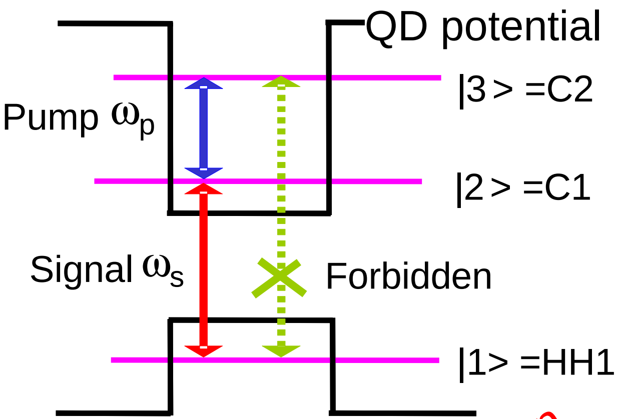
$$v_g = \frac{c}{n + \omega_S \left.\frac{\partial n}{\partial \omega}\right|_S}$$

Slow Light Using EIT

State	Reference	Material System	Temp	Results
Gas	Hau, *et.al.* 1999; Liu et. al. 2001	Sodium Atoms (Λ-type)	0.9 μK	Slow down to 17 m/s; Store light pulse for 100 usec.
Gas	Phillips et. al. 2001	Rubidium Atoms (Λ-type)	343-363 K	Halt light for 200 usec
Solid	Ham et. al. 1997	Pr-doped Y_2SiO_5 (Λ-type)	5.5K	EIT observation in solids
Solid	Turukhin et. al. 2002	Pr-doped Y_2SiO_5 (Λ-type)	5K	Slow down to 45 m/s
Semiconductor	Serapiglia et. al. 2000	InGaAs/In AlAs QWs; intersubband (ladder)	30K	Observation of reduction of absorption as signature of EIT
Semiconductor	Phillips and Wang, 2003	GaAs QWs; interband (V-type)	10 K	Observation of reduction of absorption as signature of EIT

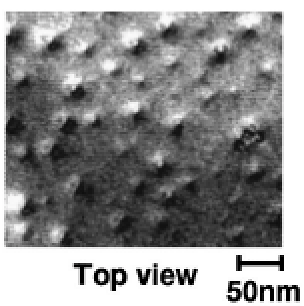
Slow Light Quantum Dot Waveguide w. Electromagnetically Induced Transparency

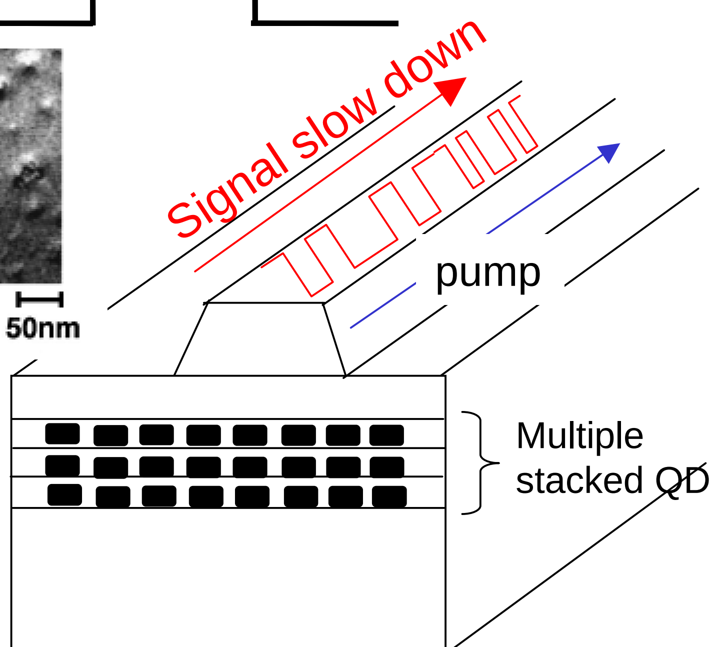
Ladder Energy Configuration

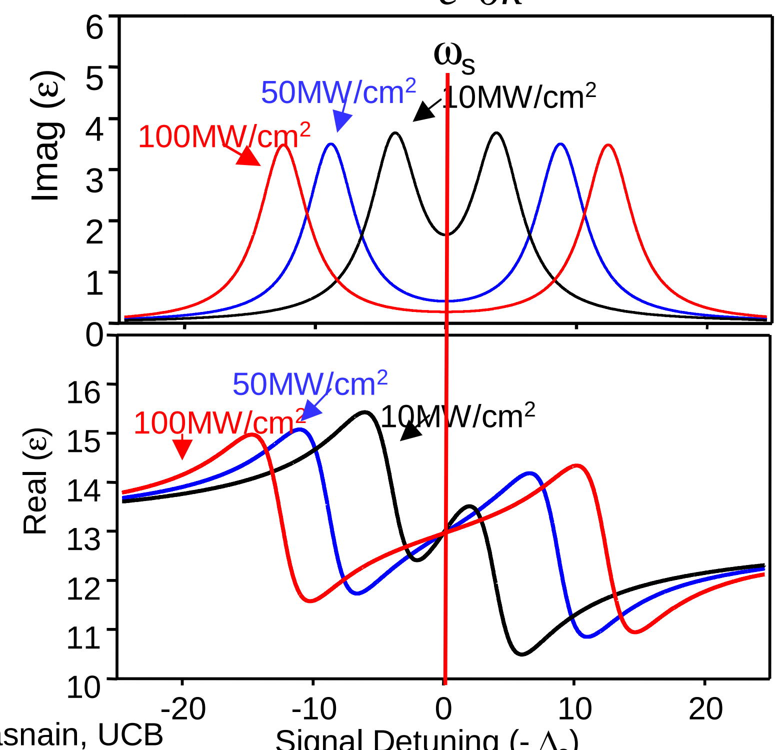


- Coherence interference between the pump laser and electronic states results in drastic change of material dispersion, known as EIT which leads to a very large slow down factor, 10^2-10^4.

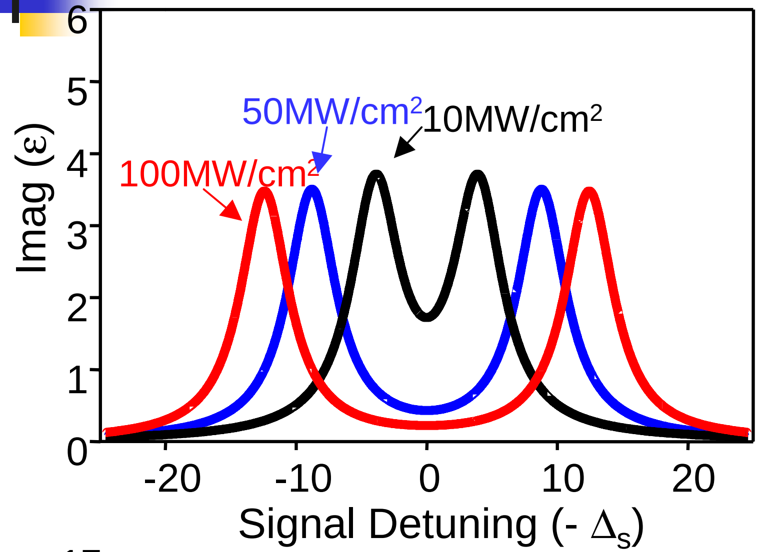
$$S = \frac{c}{v_g} = \frac{n + \omega \frac{\partial n}{\partial \omega}}{1 - \frac{\omega}{c}\frac{\partial n}{\partial k}}$$





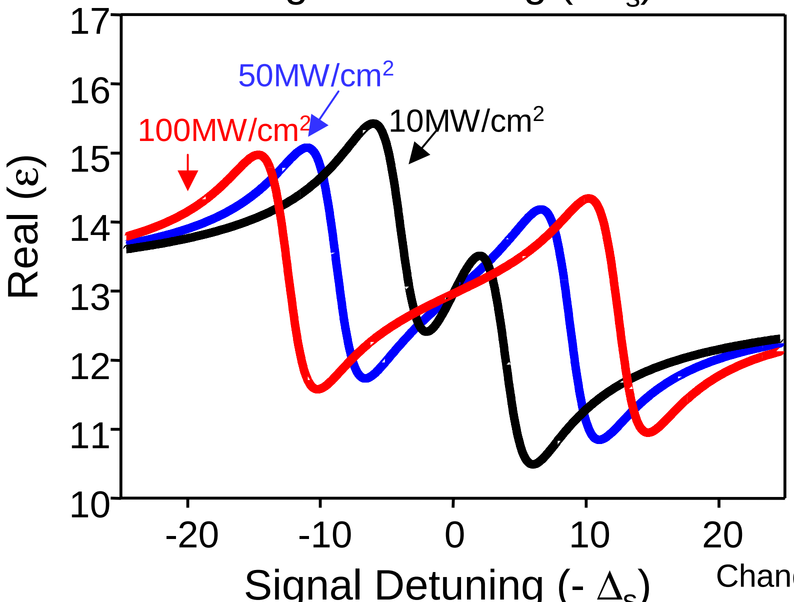


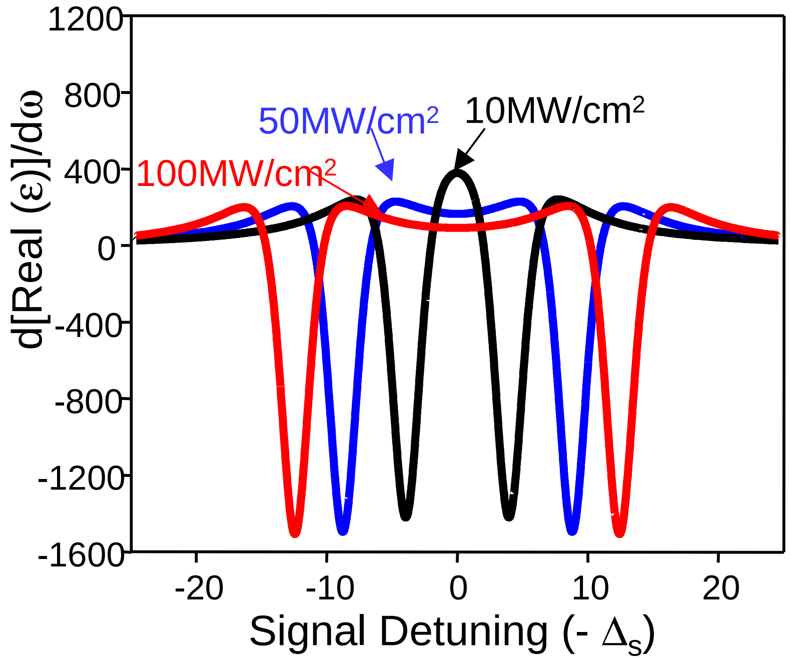
Dispersion Curves for QDs with Room Temperature Linewidths



$$\gamma_{ph} = 2.27meV$$

$$\gamma_H = 5.54meV$$





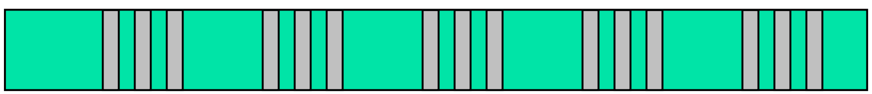
Slow Light Device Using Waveguide Dispersion

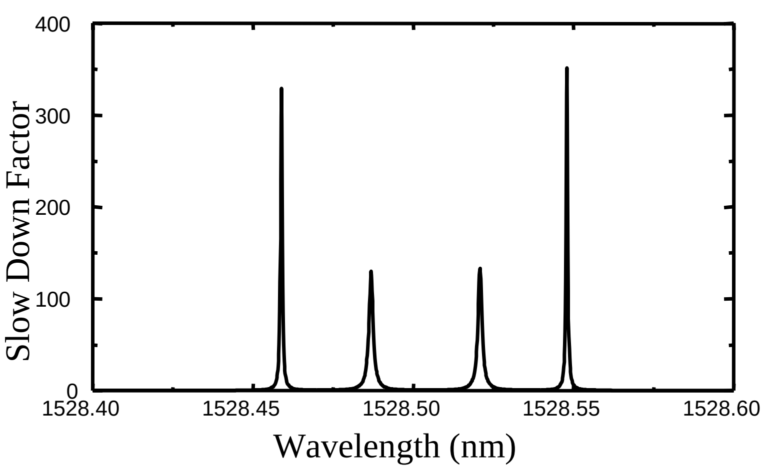
- Waveguide propagation constant k varies with frequency ω → Waveguide dispersion
- Challenges: obtaining a reasonable bandwidth and minimized dispersion

$$S = \frac{c}{v_g} = \frac{n + \omega \frac{\partial n}{\partial \omega}}{1 - \frac{\omega}{c}\frac{\partial n}{\partial k}}$$

Example 1: Sampled Gratings

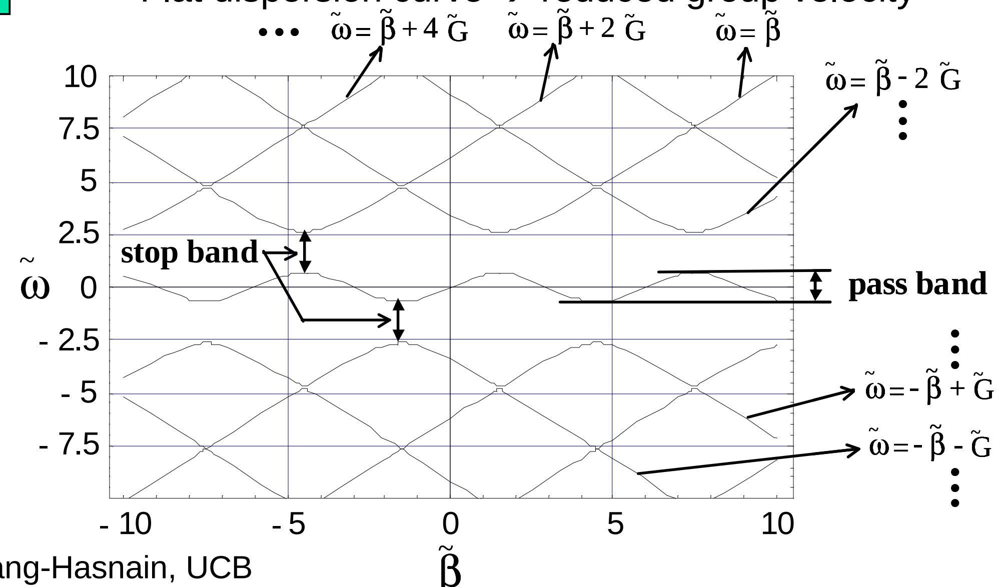
- Uniform grating regions separated by spacers
- Previous demonstration of slow down factor ~3
- Simulations show it can be increased to 100-300





Example 2: Moiré Gratings

- Two overlayed gratings with slightly different periods
- Large (x1000) group velocity reduction is predicted
  - Narrow transmission band opens within the overlap of grating stop bands
  - Flat dispersion curve → reduced group velocity

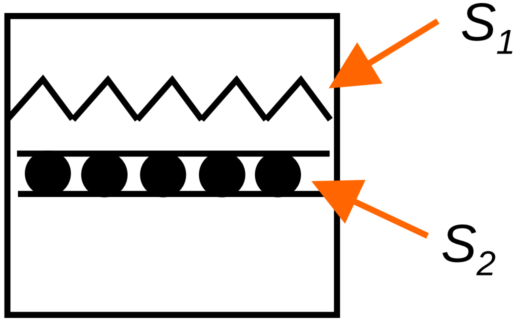


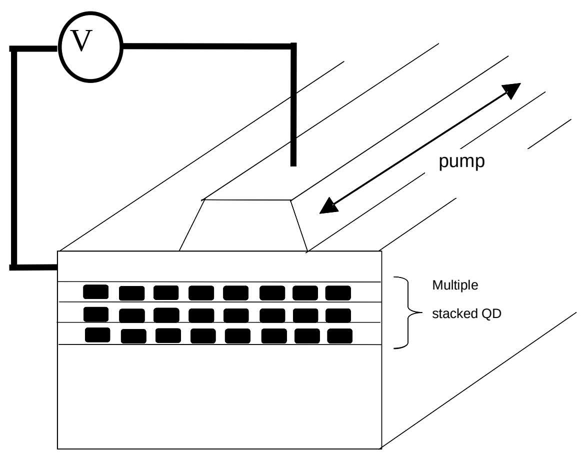
Slow Light

- Cascadable slow-down factor

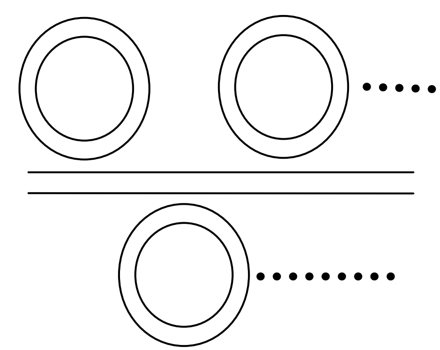
$$S=\frac{c}{v_g}=\frac{n+\omega\frac{\partial n}{\partial \omega}}{1-\frac{\omega}{c}\frac{\partial n}{\partial k}}=\underbrace{\left(n+\omega\frac{\partial n}{\partial \omega}\right)}_{S_1}\times\left(1-\underbrace{\frac{\omega}{c}\frac{\partial n}{\partial k}}_{S_2}\right)^{-1}=S_1\times S_2$$

S_1 Material dispersion $\quad$ S_2 Waveguide dispersion





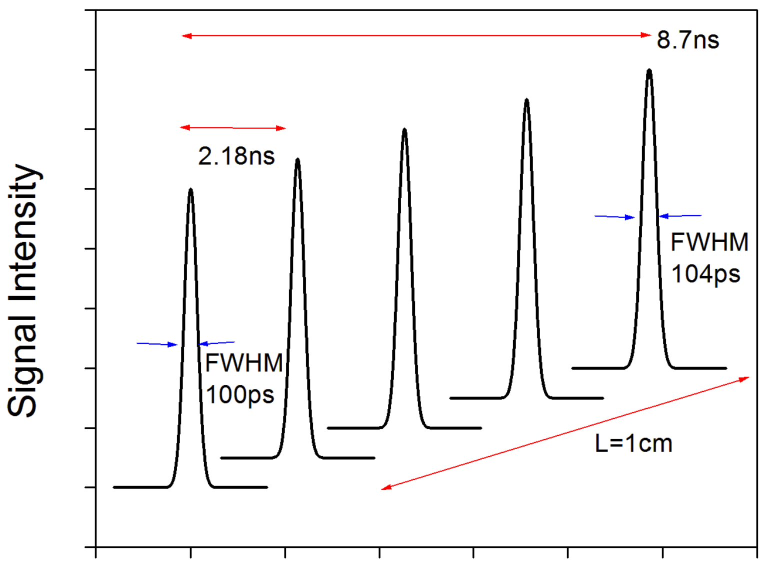
(a)



(b)

Ku et. al. “Semiconductor All-Optical Buffers Using Quantum Dots in Resonator Structures “OFC 2003

Signal Propagation



- 100 ps pulses
- Length = 1 cm
- 8.7 ns storage
- Minimum distortion and dispersion

$\gamma_{21}=\gamma_{31}=$ 2 meV

T= 300K

Summary

- Proposed and analyzed the first semiconductor all-optical buffer based on EIT effect in QDs.
- Establish the conditions and formulation necessary to achieve a large slow-down factor.
- The effect of QD size nonuniformity is also calculated. Our calculations show that a slow down factor of 50-100 can be obtained with state-of-the-art QDs at room temperature.
- S is expected to increase with
  - More uniform QDs
  - Narrower homogeneous linewidth
  - Different energy configuration